

# Dead Zones In Circumplanetary Discs as Formation Sites For Regular Satellites

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## ABSTRACT

Regular satellites in the solar system are thought to form within circumplanetary discs. We consider a model of a layered circumplanetary disc that consists of a nonturbulent midplane layer and strongly turbulent disc surface layers. The dead zone provides a favorable site for satellite formation. It is a quiescent environment that permits the growth of solid bodies. Viscous torques within the disc cause it to expand to a substantial fraction of its Hill radius ( $\sim 0.4R_H$ ) where tidal torques from the central star remove its angular momentum. For certain parameters, the dead zone develops into a high density substructure well inside the Hill sphere. The radial extent of the dead zone may explain the compactness of the regular satellites orbits for Jupiter and Saturn. The disc temperatures can be low enough to be consistent with the high ice fractions of Ganymede and Callisto.

**Key words:** accretion, accretion discs – planets and satellites: formation – planetary systems

## 1 INTRODUCTION

After a planet forms in a circumstellar disc and before its mass reaches a value of Jupiter’s mass, tidal forces from the planet open a gap in the disc (Lin & Papaloizou 1984, 1986; D’Angelo, Henning & Kley 2002; Bate et al. 2003). The planet continues to accrete material from the circumstellar disc through the gap and a circumplanetary disc forms (Artymowicz & Lubow 1996; Lubow, Seibert & Artymowicz 1999; D’Angelo, Henning & Kley 2003; Ayliffe & Bate 2009). A circumplanetary (spin-out) disc may also form if the planet manages to achieve break-up velocities as it contracts (Korycansky, Bodenheimer & Pollack 1991). The regular satellites in the solar system have prograde, nearly circular, and nearly coplanar orbits. They are thought to have formed in a circumplanetary disc, in analogy with the formation of planets in the solar nebula (Pollack, Lunine & Tittlemore 1991). Understanding the structure of these discs is essential for explaining regular satellite formation.

There are several key constraints that various models of gaseous circumplanetary discs have attempted to satisfy. The regular satellites around Jupiter and Saturn lie within a radius of less than  $0.06R_H$  of their Hill (tidal) radii  $R_H$ . The small extent of this region has been explained to be a consequence of a compact disc structure or substructure. Various studies have tied the compactness to the level of angular momentum of accreting material entering a planet’s Hill sphere (e.g., Estrada et al. 2009; Ward & Canup 2010). The idea is

that if the accreting inflow has sufficiently low angular momentum per unit mass, then the satellites formed with a circumplanetary disc will occupy a small region within the Hill sphere.

All hydrodynamics simulations of gas flows about a Jupiter mass planet have revealed a disc that is considerably more extended than the Galilean satellites. The recent study by Ayliffe & Bate (2009) shows that the disc extends to about  $0.35R_H$ . For a planet such as Jupiter that opens a gap in the circumstellar disc, gas enters the Hill sphere preferentially near the Lagrange points and carries significant angular momentum. However, the main issue is that the compactness of a fully turbulent disc cannot be maintained due to the action of viscous torques (Ward & Canup 2010; Martin & Lubow 2011a). These torques cause a compact circum-Jovian disc to rapidly expand in only  $\sim 100$  planet orbital periods for typical disc parameters.

Although the angular momentum of the inflowing gas is uncertain, the radial extent of the disc is largely independent of this quantity (Martin & Lubow 2011a). The disc expands to a radius where the tidal torques from the central star (Sun) remove angular momentum at the rate it is supplied by inflowing gas. This radius is estimated as about  $0.4R_H$ , where ballistic periodic orbits begin to cross (Martin & Lubow 2011a). (Some departures from this value occur due to pressure effects.) In addition, no compact substructure is found to lie within such a circumplanetary disc (Estrada et al. 2009; Ayliffe & Bate 2009; Martin & Lubow 2011a). With this simple alpha disc model, the turbulent

viscosity is by assumption a smooth function of radius. The disc structure then follows that of a standard smooth accretion disc.

Previous work such as Canup & Ward (2002) suggested that if the inflowing angular momentum is small enough, the flow may penetrate deep into the Hill sphere before initially collecting into a disc. If the disk is viscous, its gas component will then spread outward to a large radius. But the solids initially delivered with the gas may not be effectively coupled to the gas if they rapidly accrete and grow once in circumplanetary orbit. The solids then accrete near the compact region where they were initially delivered, rather than tracking the outward viscous expansion of the gas disk.

There are some issues of concern with this picture. The inflow may be largely planar and join the circumplanetary disk at its outer edge, as indicated by simulations by Ayliffe & Bate (2009). The gas and coupled solids would then not be able to penetrate deeply within the Hill sphere. Instead, they achieve Keplerian orbits near the outer edge of the pre-existing disk as they become entrained there. It is possible that larger size solid bodies that are decoupled from the gas could enter the Hill sphere with sufficiently low angular momentum to be captured close to the planet. But it is not clear that such a low angular momentum occurs. In this paper, we suggest an alternative explanation for the compactness of the satellites based on the radial extent of a dead zone, a region of low disc turbulence.

Another constraint applies to the disc temperature. This snow line plays an important role in the composition of forming satellites. Outside of the snow line, the solid mass density is much higher because of water ice condensation. The snow line occurs at a temperature,  $T_{\text{snow}}$ , that is around 170 K (Hayashi 1981; Lecar et al. 2006). Ganymede and Callisto, the two outer Galilean satellites contain a substantial fraction of ice ( $\sim 50\%$ ), while the two inner satellites contain much less. The snow line of the disc is then required to have been near the orbits of these outer satellites. The partially differentiated structure of Callisto suggests that its ice never fully melted and that the snow line was always inside its orbit (Lunine & Stevenson 1982). Since the disc temperature increases with mass accretion rate, this constraint limits that rate. This requirement implies that the disc accretion rates be sufficient low, substantially lower than what would be expected during the T Tauri accretion phase (Canup & Ward 2002; Estrada et al. 2009). The satellite formation epoch is therefore expected to occur late in the life of the solar nebula, when it has lost a substantial fraction of its mass.

Another issue involved in the formation of both planets and satellites in gaseous discs is the permitted level of turbulence. Estimates of disc turbulence from simulations and properties of observed systems suggest that relatively high levels of turbulence  $\alpha \sim 0.01 - 0.3$  are expected in fully turbulent discs (e.g., King, Pringle & Livio 2007). Larger solid bodies may form from the gravitational instability of a dense layer of dust that settles near the disc mid-plane (e.g., Goldreich & Ward 1973). Even modest levels of turbulence, involving  $\alpha \ll 0.01$ , can prevent solids from settling to a thin enough layer near disc mid-plane for gravitational instability to operate (Dubrulle et al. 1995; Cuzzi & Weidenschilling 2006). An alternative model for the growth of solids involves the concentration of dust in turbulent eddies (Cuzzi et al. 2008). This model also adopted a weaker level of turbulence.

Another effect is that turbulence can cause destructive collisions among larger solid bodies, thereby preventing growth to the desired size (e.g., Ida, Guillot, & Morbidelli 2008). These results suggest that lower values of disc turbulence may be more favorable for satellite formation than is occurs in a fully turbulent disc.

In a layered disc, the magnetic turbulence (MRI; Balbus & Hawley 1991) is not active at all heights (Gammie 1996). Magnetic turbulence requires a certain level of ionization for the gas to be well enough coupled to the magnetic field. In sufficiently cool disc regions, temperatures are too low to provide the needed level of the ionization for magnetic turbulence to operate. Instead, the ionization is provided by external sources of radiation, such as X-rays or cosmic rays. If the disc surface density is high enough, this radiation may not penetrate deep enough below the disc surfaces to provide turbulence at all heights. A so-called dead zone with little or no turbulence develops around the disc midplane. Such an environment may be favorable for the survival and growth of solid bodies.

In an earlier paper, we explored a layered disc model for the evolution of a circumplanetary disc during a stage when the disc experiences accretion rates comparable to those of the T Tauri phase (Lubow & Martin 2012). Such discs can sometimes undergo outbursts, analogous to the FU Ori outbursts. In any case, such a disc is too hot for the survival of icy satellites at the locations of Ganymede and Callisto.

We explore in this paper the viability of a layered disc model as an environment for satellite formation in later stages of its evolution. We do not attempt to model the formation of satellites in such a disc. Instead, we show that in this stage and for certain plausible disc ionization parameters, a layered disc model satisfies the requirements described above. In particular, a compact high density disc substructure develops in a low turbulence dead zone whose extent matches that of the regular satellites. The disc temperature is low enough for the outermost Galilean satellites to lie outside the snow line.

In Section 2, we describe the results from our circumplanetary disc model and how it may explain some features of the formation of the Galilean satellites. In Section 3 we discuss some implications and limitations of the model and in Section 4 we draw our conclusions.

## 2 CIRCUMPLANETARY DISC MODEL

In this Section we first describe our layered circumplanetary disc model that is truncated by tides from the star and then we discuss the results.

### 2.1 Model Description

We use the layered disc model initially described in Armitage, Livio, & Pringle (2001) and further developed in Zhu et al. (2009), Martin & Lubow (2011b) and Lubow & Martin (2012). Material in the circumplanetary disc orbits the central planet of mass  $M_p$  at Keplerian angular speed  $\Omega(R) = \sqrt{GM_p/R^3}$  for radius  $R$  from the planet. Material is added to the disc at rate  $\dot{M}_{\text{infall}}$ . The disc has a total surface density  $\Sigma(R, t)$ , midplane temperature  $T_c(R, t)$ , and surface temperature  $T_e(R, t)$  at time  $t$ .

The MRI turbulent surface layer (which we call the active layer) has surface density  $\Sigma_m(R, t)$ , temperature  $T_m(R, t)$ , and turbulent viscosity  $\nu_m(T_m, R, t)$  that is parametrised with the Shakura & Sunyaev (1973)  $\alpha_m$  parameter. Cosmic rays and/or X-rays are assumed to be able to provide sufficient ionization for MRI to operate to a constant surface density depth  $\Sigma_{\text{crit}}$ . If the total surface density is greater than this critical value,  $\Sigma > \Sigma_{\text{crit}}$ , then  $\Sigma_m = \Sigma_{\text{crit}}$ . For smaller surface density,  $\Sigma < \Sigma_{\text{crit}}$ , the disc is fully MRI active and  $\Sigma_m = \Sigma$ .

A complementary midplane layer exists if the total surface density is larger than the critical,  $\Sigma > \Sigma_{\text{crit}}$ . It has surface density  $\Sigma_g = \Sigma - \Sigma_{\text{crit}}$  and midplane temperature  $T_c$ . This layer is MRI active if the midplane temperature is greater than the critical,  $T_c > T_{\text{crit}}$ , where  $T_{\text{crit}}$  is the temperature for sufficient thermal ionisation. However, for lower temperatures,  $T_c < T_{\text{crit}}$ , a dead zone forms. In the model, there is no turbulence in the dead zone unless it is massive enough to be self-gravitating. (In reality, some turbulence is expected due to the vertical propagation of waves from the active layer (Fleming & Stone 2003).) The condition for self gravity is taken to be that the Toomre parameter is smaller than its critical value,  $Q < Q_{\text{crit}} = 2$  (Toomre 1964). In this case, a second viscosity term is included in the complementary layer.

We consider the planet Jupiter with mass,  $M_p = 1 M_J$ , that is orbiting the Sun,  $M = 1 M_\odot$ , at a distance of  $a = 5.2$  AU. We solve the accretion disc equations numerically on a fixed mesh that is uniform in  $\log R$  with 120 grid points (e.g., Armitage, Livio, & Pringle 2001; Martin et al. 2007). The inner boundary has a zero torque condition at the radius of Jupiter,  $R = 1 R_J$ , so the mass falls freely on to the planet. At the outer boundary we approximate the tidal torque from the star with a zero radial velocity boundary condition at  $R_{\text{out}} = 0.4 R_H$ . Material accretes on to the disc at a constant rate  $\dot{M}_{\text{infall}}$  at a radius which we take to be  $0.33 R_H$  (see Lubow & Martin 2012, for more explanation). Initially, we take the surface density and temperature structure of the disc to be that of low mass (nonself gravitating) disc with a small dead zone. This state represents the disc immediately following an outburst. Alternatively, if there is initially no mass in the disc, it quickly builds up to the same state.

The critical surface density that is sufficiently ionised to be turbulent,  $\Sigma_{\text{crit}}$ , is not well determined. When cosmic rays are the dominant source of ionisation, for typical parameters the surface turbulent layer of a circumstellar disc has been estimated to have a surface density of  $\Sigma_{\text{crit}} \approx 200 \text{ g cm}^{-2}$  (Gammie 1996; Fromang, Terquem & Balbus 2002). However, it is possible that cosmic rays are swept away from the disc by means of a turbulent MHD jet or outflow which may be present at the star (e.g. Skilling & Strong 1976; Cesarsky & Völk 1978). In the absence of cosmic rays, X-rays from the star may be the dominant source of ionisation and in this case the active layer is much smaller (Matsumura & Pudritz 2003).

More recent works find the inclusion of polycyclic aromatic hydrocarbons and dust tends to suppress the instability further (Bai & Goodman 2009; Perez-Becker & Chiang 2011; Bai 2011; Fujii, Okuzumi & Inutsuka 2011). However, in circumstellar discs, such effects produce an accretion rate that is too low to account for T Tauri accretion rates and this problem remains unsolved. Perez-Becker & Chiang

(2011) suggest that in order to explain the T Tauri rates,  $\Sigma_{\text{crit}} > 10 \text{ g cm}^{-2}$ , in the circumstellar disc. It is possible that circumplanetary discs may have an even smaller active layer surface density than circumstellar discs, since they may be shielded from the ionising radiation of the central star by the shadowing effects of the inner circumstellar disc. Because of these uncertainties, we follow the work of Armitage et al (2001) and Zhu et al. (2009) and regard  $\Sigma_{\text{crit}}$  as a constant free parameter. If the critical surface density is large, then the entire disc will be fully turbulent. If it is small, then the dead zone will be very extensive. We consider a range of active layer surface densities with  $1 \text{ g cm}^{-2} \leq \Sigma_{\text{crit}} \leq 100 \text{ g cm}^{-2}$ .

Generally, we take the value of the temperature for sufficient thermal ionization for MRI to operate to be  $T_{\text{crit}} = 800 \text{ K}$ . At this temperature the ionisation fraction increases exponentially with temperature due to the collisional ionisation of potassium (Umebayashi 1983). The viscosity  $\alpha_m$  parameter associated with MRI is found to be  $\gtrsim 0.01$  from MHD simulations, but depends on numerous parameters such as the resolution, stratification, and treatments of small scale dissipation and radiation transport (e.g. Hartmann et al. 1998; Fromang et al. 2007; Guan et al. 2009; Davis et al. 2009). Similarly, observations of FU Ori suggest that  $\alpha_m \approx 0.01$  (Zhu et al. 2007). However, observations of X-ray binaries and dwarf novae suggest  $\alpha_m \approx 0.1 - 0.4$  (King, Pringle & Livio 2007). Armitage et al (2001) take  $\alpha_m = 0.01$  and Zhu et al. (2010) consider both 0.01 and 0.1. With the uncertainty in the value, we also consider cases with both  $\alpha_m = 0.01$  and 0.1.

During times of planet formation, the accretion rate on to the circumplanetary disc,  $\dot{M}_{\text{infall}}$ , is of order the overall circumstellar disc accretion rate (Bate et al. 2003; Lubow & D'Angelo 2006; Ayliffe & Bate 2009) that is of order  $10^{-8} M_\odot \text{ yr}^{-1}$  (Valenti, Basri & Johns 1993; Hartmann et al. 1998), typical for the T Tauri phase. During this phase, disc temperatures are too high to permit the survival of ice in Callisto (Canup & Ward 2002; Estrada et al. 2009). Consequently, we consider the evolution in the later stages of disc evolution, when the accretion rate has dropped by an order of magnitude or more. We consider accretion rates in the range  $10^{-11} - 10^{-9} M_\odot \text{ yr}^{-1}$  near the end of the disc lifetime.

If the circumplanetary disc density in the dead zone grows sufficient large during the T Tauri stage, the disc becomes gravitationally unstable. Self-gravity generates turbulence that raises the disc midplane temperature (e.g., Lodato & Rice 2004). If the temperature exceeds the critical value  $T_{\text{crit}}$  for sufficient thermal ionization for MRI to operate, MRI can set in abruptly and lead to a gravo-magneto accretion outburst in a circumplanetary disc (Lubow & Martin 2012). These conditions involve high disc temperatures. The dead zone structure is disrupted and dead zone mass is accreted on the central planet. The process repeats and can be described as a limit cycle of the gravo-magneto instability (Martin & Lubow 2011b). Consequently, we regard the T Tauri stage as unfavorable for satellite formation or survival.

As the disc disperses near the end of its lifetime, the accretion rate  $\dot{M}_{\text{infall}}$  decreases and outbursts become less likely. We are most interested in models that have a long outburst interval timescale. The outburst interval timescale

increases with decreasing accretion rate. If the mass accretion rate decreases substantially after an outburst, then the outburst may not recur. The lifetime of the circumplanetary disc is assumed to be similar to that of the circumstellar disc, a few  $10^6$  yr. A simple estimate for the outburst timescale is the timescale for the disc to become self gravitating. This timescale can be estimated as the time to build up a mass of  $M_p H/R$ , where  $H = c_s/\Omega$  is the disc scale height and  $c_s$  is the sound speed. This mass is at most around a few tenths of a Jupiter mass. The outburst interval timescale is of order

$$t_{\text{int}} \approx \frac{M_p}{\dot{M}_{\text{infall}}} \frac{H}{R}. \quad (1)$$

## 2.2 Model Results

Table 1 summarizes simulation results for a range of parameters that cover some plausible values for the viscosity parameter  $\alpha_m$  and the critical surface density for ionization  $\Sigma_{\text{crit}}$ . In Fig. 1 we show the surface density and temperature distributions for models with  $\alpha_m = 0.01$  and  $\dot{M}_{\text{infall}} = 10^{-10} M_\odot \text{ yr}^{-1}$ . Model R8 is fully turbulent and this steady solution holds for  $\Sigma_{\text{crit}} > 27.1 \text{ g cm}^{-2}$ . Model R9 has critical surface density  $\Sigma_{\text{crit}} = 10 \text{ g cm}^{-2}$  and hence contains a dead zone. Within the dead zone, the surface density increases substantially with time. For Model R9 this region extends to radius  $R_{\text{dead}} = 0.034 R_H$ . This location is close to the orbit of Callisto. Such a model may explain why Callisto has a large mass and angular momentum, yet no satellites are found outside of its orbit. Beyond the dead zone, less material is available to form satellites and the turbulence may disrupt the growth into larger bodies.

At later times, the higher disc mass in the dead zone is in the range of the so-called minimum mass sub-nebula (MMSN) (Lunine & Stevenson 1982). However, the model here is fundamentally different from a static MMSN that was initially envisioned by some earlier work, because it considers a continuously supplied disc. The accretion time scale in this paper is regulated by the inflow rate to the disc, as in the original continuous inflow concept of (Canup & Ward 2002).

The disc structure we obtain is similar to the gas rich disc model envisioned by Mosqueira & Estrada (2003a) and Estrada et al. (2009). In their model, Callisto lies just outside the dense inner disc, the dead zone in the current model. They suggested that Callisto's inferred long formation timescale (Stevenson, Harris & Lunine 1986), which caused its partial differentiation, results from the relatively slow delivery of solids in the outer disc, due to its lower density. The model also describes Ganymede as being formed more rapidly within the dense disc. These different environments provide a possible explanation for the Callisto-Ganymede dichotomy that describes the differences between these two outermost Galilean satellites (Lunine & Stevenson 1982).

The mass of the fully turbulent disc in Model R8 is  $4.3 \times 10^{-5} M_J$  whereas the mass of the disc with a dead zone in Model R9 at a time of  $10^5$  yr is  $9.1 \times 10^{-3} M_J$ . The dead zone model has a lower temperature distribution than the fully turbulent model. For example, the snow line location changes from  $0.032 R_H$  in the fully turbulent model to  $0.017 R_H$  when a dead zone is introduced. The latter snow

line location is in the range expected for the survival of ice in Callisto. The outburst intervals for Model R9 at constant accretion rate are also fairly long. For model R9,  $H/R < 0.2$  and so the outburst timescale is around  $2 \times 10^6$  yr.

With a higher accretion rate of  $10^{-9} M_\odot \text{ yr}^{-1}$ , the disc builds up mass very quickly and so the outburst time scale is fairly short. In addition, it is difficult to simultaneously meet the constraints on the snow line location and the compactness of the dead zone. The models that best meet these requirements, Models R9 and R12, have the intermediate accretion rate  $\dot{M} = 10^{-10} M_\odot \text{ yr}^{-1}$ .

We note that because of the dead zone, the vertically averaged  $\alpha$  in the disc is much lower than the value in the active layer of 0.01 or 0.1. In some ways this vertical average approximates the  $\alpha$  value adopted by Canup & Ward (2002). However, since that model does not have a dead zone, there is no accumulation of mass that produces the compact disc substructure. Fully turbulent models with lower accretion rates of  $10^{-11} M_\odot \text{ yr}^{-1}$  (R13 and R14) have low enough temperatures for icy satellite formation (as found by Canup & Ward 2002).

## 3 DISCUSSION

There are several approximations in the layered disc model we have considered that should be improved on in future work. Some of these were discussed in Martin & Lubow (2011b) and Lubow & Martin (2012). For example, we have approximated the surface density in the active layer as a constant with radius in the disc. An alternative method of finding the dead zone is with a critical magnetic Reynolds number (e.g. Fromang, Terquem & Balbus 2002; Matsumura & Pudritz 2003). In this approach, the surface density of the turbulent layer may vary in radius (Martin et al. 2012a). However, there are currently still problems with this model, as it is difficult to explain T Tauri accretion rates with a low critical surface density (Martin et al. 2012b).

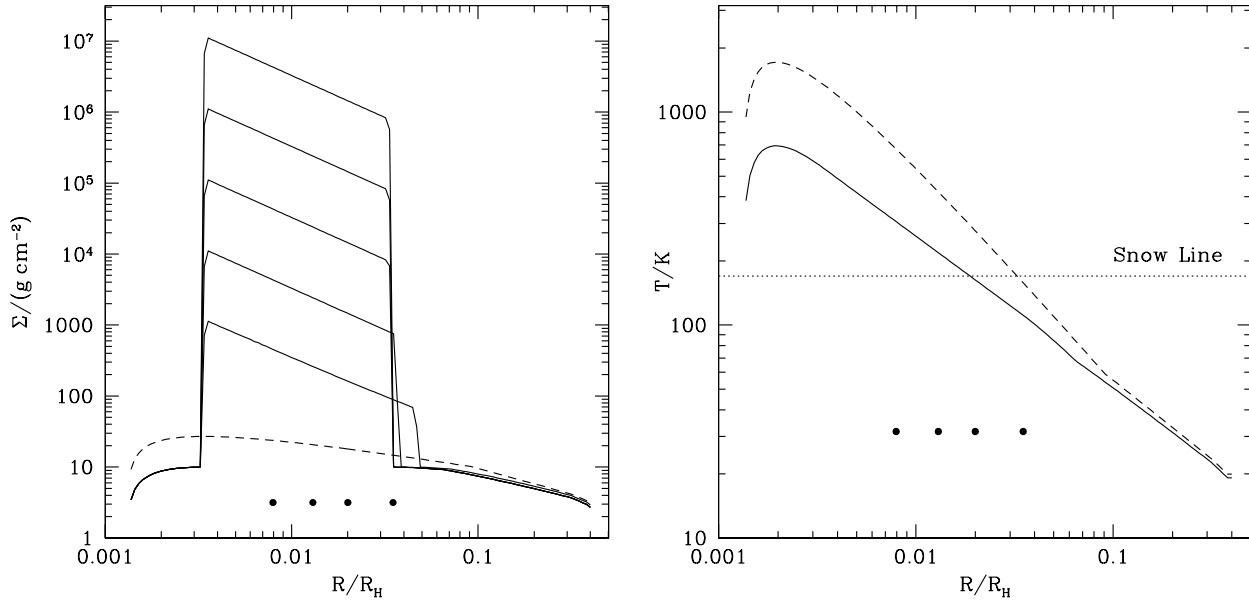
The infall accretion rates we considered are constant in time. However, they are likely to decrease as the flow through the circumstellar disc decreases. As the accretion rate decreases, the active surface layer occupies an increasing fraction of the vertical extent of the disc. When the accretion rate drops to values of  $\lesssim 10^{-11} M_\odot \text{ yr}^{-1}$ , the disc will become fully turbulent with the adopted parameters (Models R13 and R14). The disc temperatures remain low enough for the survival of ice in Callisto.

The inferred density of the small inner Jovian satellite Amalthea suggests that contains a substantial fraction of water-ice (Anderson et al. 2005). Accretion disc models, such as the one described here, predict that temperatures are too high for the water-ice to survive and requires some other explanation.

Another open issue is satellite survival in such a high density disc against the effects of orbit decay due to disc-satellite interactions (Ward 1997; Lubow & Ida 2010). The Type I migration timescale in the dead zone of model R9 is quite short  $\sim 10^2$  yr (Canup & Ward 2002). It is possible that the satellites instead undergo the potentially slower Type II migration, provided that they can open gaps. Gap opening in a low viscosity disc is dominated by effects of gas

Model	$\dot{M}_{\text{infall}}$ ( $M_{\odot} \text{ yr}^{-1}$ )	$\alpha_m$	$\Sigma_{\text{crit}}$ ( $\text{g cm}^{-2}$ )	$R_{\text{dead}}$ ( $R_H$ )	$R_{\text{snow}}$ ( $R_H$ )	$M_{\text{disc}}(t = 10^5 \text{ yr})$ ( $M_J$ )	Outburst Timescale (yr)
R1	$10^{-9}$	0.01	$> 90.3$	-	0.094	$1.9 \times 10^{-4}$	Steady
R2	$10^{-9}$	0.01	40	0.023	0.084	$6.7 \times 10^{-2}$	$1.4 \times 10^5$
R3	$10^{-9}$	0.01	10	0.32	0.019	$1.0 \times 10^{-1}$	$7.8 \times 10^5$
R4	$10^{-9}$	0.01	1	0.33	0.0023	$1.1 \times 10^{-1}$	$8.3 \times 10^5$
R5	$10^{-9}$	0.1	$> 15.6$	-	0.056	$2.5 \times 10^{-4}$	Steady
R6	$10^{-9}$	0.1	10	0.0097	0.052		$> 10^5$
R7	$10^{-9}$	0.1	1	0.32	0.011	$1.0 \times 10^{-1}$	$> 10^5$
R8	$10^{-10}$	0.01	$> 27.1$	-	0.032	$4.3 \times 10^{-5}$	Steady
<b>R9</b>	<b><math>10^{-10}</math></b>	<b>0.01</b>	<b>10</b>	<b>0.034</b>	<b>0.017</b>	<b><math>9.1 \times 10^{-3}</math></b>	<b><math>&gt; 10^6</math></b>
R10	$10^{-10}$	0.01	1	0.32	0.0023	$1.1 \times 10^{-2}$	$> 10^6$
R11	$10^{-10}$	0.1	$> 4.7$	-	0.021	$4.5 \times 10^{-6}$	Steady
<b>R12</b>	<b><math>10^{-10}</math></b>	<b>0.1</b>	<b>1</b>	<b>0.035</b>	<b>0.011</b>	<b><math>9.8 \times 10^{-3}</math></b>	<b><math>&gt; 10^6</math></b>
R13	$10^{-11}$	0.01	$> 8.1$	-	0.011	$7.7 \times 10^{-6}$	Steady
R14	$10^{-11}$	0.1	$> 1.2$	-	0.0092	$7.8 \times 10^{-7}$	Steady

**Table 1.** Column 2 contains the infall accretion rate on to the circumplanetary disc, column 3 contains the viscosity  $\alpha_m$  parameter, column 4 contains the critical surface density in the active layer that is ionised by cosmic rays/X-rays, column 5 contains the outer radius of the dead zone,  $R_{\text{dead}}$ , if it exists, column 6 contains the snow line radius and column 7 contains the total mass in the disc at time  $t = 10^5$  yr. If the disc has a dead zone, then the mass of the disc increases linearly in time. But if there is no dead zone, then the mass is constant. Finally, column 8 contains estimates of the timescales for the gravo-magneto outbursts.



**Figure 1.** Left: The surface density of the disc in model R8 (dashed line) and R9 (solid lines) at times  $t = 10^2, 10^3, 10^4, 10^5$  and  $10^6$  yr in order of increasing height in the plot. As the dead zone gains mass, its surface density grows in time. Right: The midplane temperature of the disc in R9 (solid line) and R8 (dashed line). The temperature in model R9 does not change in time even though the surface density does. The dotted line shows the snow line temperature,  $T_{\text{snow}} = 170$  K. The solid circles in both plots show the radial locations of the Galilean satellites.

shocks caused by the steepening of density waves (Rafikov 2002; Yu et al. 2010). The gap opening condition in this case suggests that Callisto and Ganymede can open gaps for Model R9, but only for  $\Sigma \lesssim 10^4 \text{ g cm}^{-2}$ .

The nature of gap opening and migration in a layered disc has not been examined. The application of the viscous gap opening criterion (e.g., equation 5 of Canup & Ward 2002) to the active layer alone suggests that gap opening

does not occur. On the other hand, its application to a vertical averaged  $\alpha$  suggests that gap opening may occur. There are some other possibilities. If Callisto resides just outside the dead zone, it may be subject to outward Lindblad torques that stall its migration there (Mosqueira & Estrada 2003b; Matsumura, Pudritz & Thommes 2007). Trapping may also be possible at the inner edge of the dead zone (Kretke et al. 2009). We also note that outward corotation

torques could affect migration (Paardekooper & Mellema 2006), since the dead zone region in Fig. 1 has a negative radial entropy gradient that is required for this effect to operate. On the other hand, corotation torques can become quite weak and saturate in a low viscosity environment (e.g., Ward 1991; Ogilvie & Lubow 2003).

Canup & Ward (2002) point out other constraints that should be considered. One is that if satellites open gaps in the disc, then satellite eccentricities should be excited by first order Lindblad resonances. The excitation of eccentricity of planets that open gaps has been an active area of exploration (Goldreich & Sari 2003; Ogilvie & Lubow 2003). The simulation results appear to be sensitive to how clean and large the gap is. Papaloizou, Nelson, & Masset (2001) found no eccentricity growth for a  $1M_J$  which produces a fairly clean gap, but growth at much higher masses. D'Angelo, Lubow & Bate (2006) found some eccentricity growth occurred  $1M_J$ , but was quite weak compared to growth rates for higher mass planets. In any case, at late times when  $\dot{M}_{\text{infall}} \lesssim 10^{-11} M_{\odot} \text{ yr}^{-1}$ , the disc surface density in the satellite region will drop to less than critical values  $\Sigma(R) < \Sigma_{\text{crit}}$ . The disc is then fully turbulent and gap opening will not occur. The available gas at this stage may be sufficient to damp eccentricities developed in a prior open-gap stage.

The disc structure produced by this model is somewhat similar to the gas rich model described in Mosqueira & Estrada (2003a) and Estrada et al. (2009). In that model, the dense inner disc is the relic of a disc formed prior to gap opening. The low density outer disc is formed by higher angular momentum gas accreted after gap opening. It is not clear why the inner disc would not accrete onto the planet. We expect that a significant fraction of the mass of Jupiter was acquired after gap opening through disc accretion. In the present model, accreting gas builds up mass in a small inner region due to the presence of the dead zone.

The dead zone is assumed to be free of turbulence. Suppose some independent mechanism produces turbulence there that we do not take into account, such as a hydrodynamic instability not involving MRI or self-gravity. The dead zone would then achieve a steady state flow that would limit the mass growth of the dead zone as seen in Fig. 1. For the parameters adopted in Model R9, reaching the highest plotted densities requires that  $\alpha_d \sim 10^{-8}$ .

#### 4 CONCLUSIONS

We have described some possible proto-satellite environments that occur in discs with dead zones. A dead zone will occur if external radiation is insufficient to fully ionize cool regions of a disc (Gammie 1996). The dead zone provides a quiescent environment for the survival and growth of solid bodies into satellites. As the dead zone gains mass, it can provide a high density, compact substructure within the circumplanetary disc (see Fig. 1). The regular satellites of Jupiter and Saturn lie within a small fraction of their Hill radii. A fully turbulent simple alpha disc extends to much larger radii and has a smoothly varying density structure. The compactness of a high density dead zone provides a possible explanation for the small radial extent of the regular satellites. For accretion rates appropriate to the late stages

its evolution, the circum-Jovian disc can be cool enough to permit the survival of the ice in Callisto.

In this paper we have only considered possible disc structures that can arise in circumplanetary discs with dead zones. More work is required to explore the growth, survival, and evolution of satellites in such discs.

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